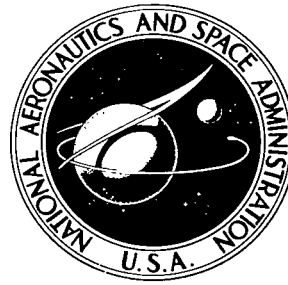


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USE OF HIGH-CONDUCTIVITY
CLADDING MATERIAL ON D-SHAPED
COOLANT PASSAGES IN NOZZLES TO
REDUCE TUBE-WALL CREST TEMPERATURES

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Cleveland, Ohio 44135



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USE OF HIGH-CONDUCTIVITY CLADDING MATERIAL ON D-SHAPED COOLANT PASSAGES IN NOZZLES TO REDUCE TUBE-WALL CREST TEMPERATURES

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SUMMARY

Calculations of wall temperatures in a rocket engine cooling tube have been made for a cooling tube with a D-shaped cross section. The hot gases flow along the semi-circular outer surface of the tube. The flat surface of the tube is insulated from the outside atmosphere. The convective heat-transfer coefficients and tube thicknesses were chosen to be typical of those in a liquid-hydrogen-cooled, liquid-oxygen - hydrogen rocket engine. The calculations were made for both copper and 347 stainless-steel tube materials and for copper-clad stainless-steel tubes. The calculations were made assuming that the convective hot gas side heat-transfer coefficient was (1) a constant and (2) varied as the cosine of the center angle measured from the tube cross section line of symmetry. For the clad cases, when the coefficient was held constant the wall temperatures were higher than when calculated with the cosine variation. This also occurred for the plain copper tube with even more marked differences.

It was found that cladding the stainless-steel tube with copper 0.229 centimeter thick lowered the tube-wall crest temperature provided the tube radius did not exceed 0.3 centimeter.

Copper tubing having a tube semicircular radius of 0.133 centimeter and a wall thickness of 0.025 centimeter will yield a tube-wall crest temperature as much as 350 K below the equivalent stainless-steel tubing temperature (787 K).

The calculations given herein illustrate general trends. Specific cases of interest to the reader should be calculated individually.

INTRODUCTION

Numerous investigations have been made into the general problem of convectively cooling the wall of a rocket engine. Curren, Price, Krueger, and Manning (ref. 1) worked with essentially rectangular cooling passages. As design cooling passage

pressures increase it is apparent that circular or near circular passages become more attractive because of strength considerations. Current engines use passage cross sections which approach circular, D-shaped, or elliptical shapes.

Dusinberre, Kimball, and Elrod (ref. 2) analyzed the case of a circular boiler tube heated by radiation over half of its outer circumference and insulated over the remaining half. They assumed no resistance to heat flow from the tube wall to the coolant which flowed through the tube; hence, the inner surface wall temperature was constant and equal to the coolant temperature. Work performed by Sellers (ref. 3) dealt with rectangular cooling tubes with convective heat transfer to one external surface of the rectangular passage. In addition, an analysis was performed by Davey (ref. 4) on a cooling tube having two semicircular end sections joined together by two flat plates forming a cross section similar to a flattened ellipse. The tube was heated convectively over one of the semicircular surfaces and cooled convectively by a fluid flowing through the inside. Half of this configuration is approximated by the D-shaped passage (fig. 1), which is the subject of this report, provided the heat conduction along the tube to the back face of the tube is negligible.

Both references 3 and 4 showed that the tube wall thickness is a major factor in the fin effectiveness of the side wall of a tubular cooling passage. In addition, reference 3 shows that the width of the cooling passage, the heat-transfer coefficients, and the thermal conductivity of the tube material are important parameters in dealing with the fin effect.

The maximum tube temperature occurs at the crest of the tube exposed to the hot gases. This tube-wall crest temperature ($\theta = 0$, fig. 1) can be reduced by using a wall material having a higher thermal conductivity or by cladding the usually low thermal conductivity tube with a coating material having a still lower conductivity but a higher temperature limit. A third alternative is to clad the tube with a high thermal conductivity material. This provides a lower resistance path for the heat to be conducted circumferentially to the regions where the tubes are brazed together increasing the temperature at the braze line and causing more heat to be conducted along the tube wall between adjacent tubes and ultimately into the coolant.

Cooling passages made by placing a high thermal conductivity material over a high strength but low thermal conductivity material (fig. 1) can approach the lower temperatures of a tube made entirely of high thermal conductivity material, thus retaining the high strength of the inner shell material. Calculations presented in this report show the magnitude of the wall temperature change caused by cladding; they also show the effect of the plain wall being made of only the high thermal conductivity material. The composite wall allows higher pressures in the coolant passage, since the high strength material will operate at a lower temperature and have greater strength and fatigue life.

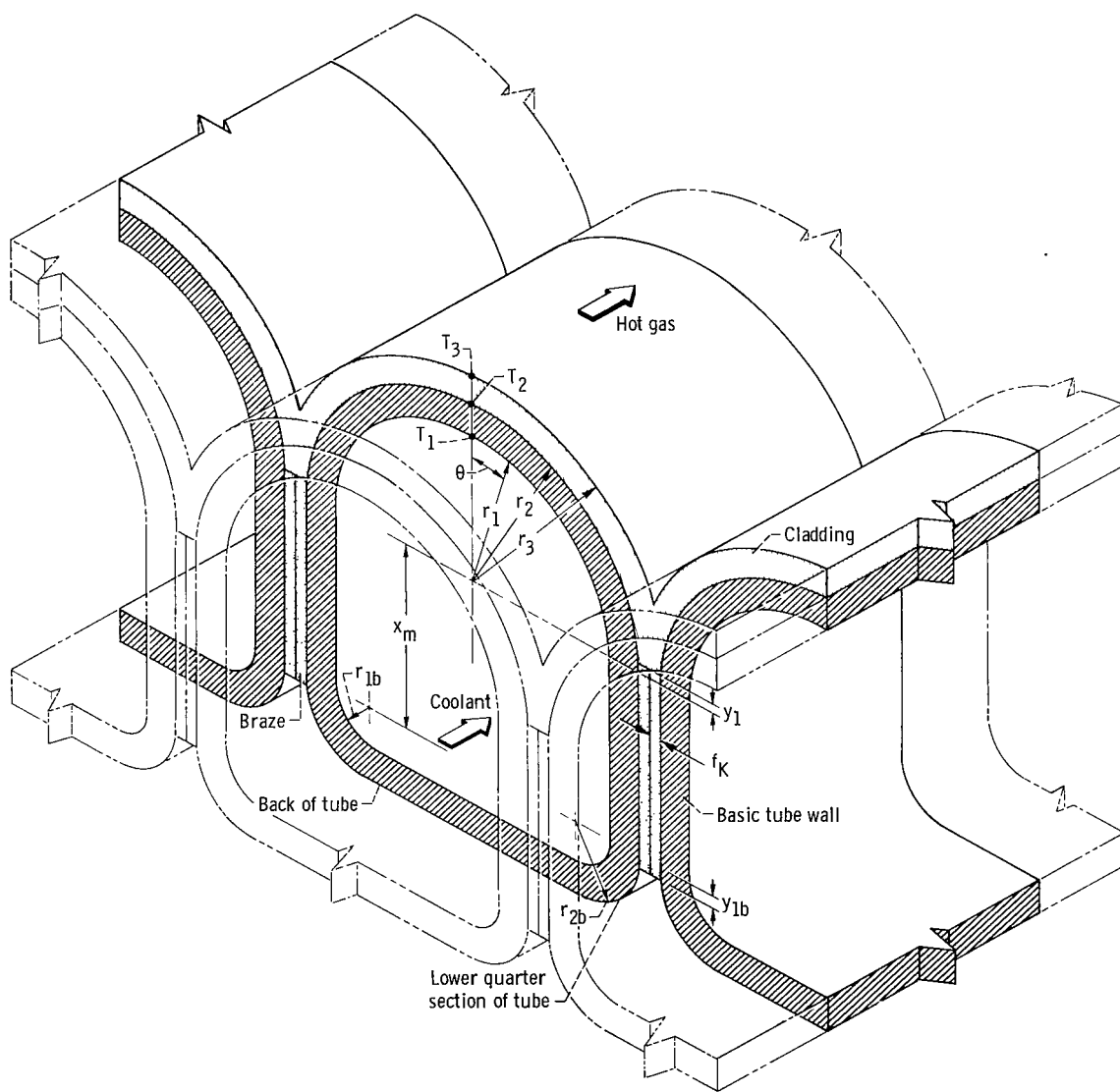


Figure 1. - Cross section of rocket engine wall made with D-shaped tubular cooling passages.

The lower wall temperature could also allow the use of thinner walls for a given pressure.

It is assumed that the high thermal conductivity cladding or wall material is compatible with the environment in which it operates. A brief discussion of the compability of copper with possible environments is presented.

This study was performed at NASA Lewis Research Center as part of a rocket heat-transfer program. A computer program (ref. 5) was developed to calculate the temperature distribution through a D-shaped cooling passage on which a cladding has been applied. Thermal conductivity as a function of temperature for both the tube and the cladding material are independent inputs to the program as are the convective heat-transfer coefficients on the tube surfaces and the coolant and hot gas temperatures. The program can be used to calculate the effect of a low thermal conductivity coating as well as a high one. In this analysis only a high thermal conductivity material for the cladding is used.

The materials used for this analysis are 347 stainless steel in the tube wall and copper in the cladding. In addition, the cases of plain tubes with copper and 347 stainless steel are evaluated. Two cases for the hot gas side convective heat-transfer coefficient are used in the calculations; in one case the coefficient is constant, while in the other the coefficient is varied as the cosine of the central angle θ measured from the D-shaped duct line of symmetry (see fig. 1). These two cases represent the extremes in the variation of the hot gas coefficient which might be expected in a tubular-walled rocket engine.

SYMBOLS

f_K	thickness of braze measured from side of rectangular tube section to line of symmetry between adjacent tubes, cm
h	convective heat-transfer coefficient, (W)/(m ²)(K)
k	thermal conductivity, (W)/(m)(K)
n	unit vector normal to local surface
r	radius, cm
T	temperature, K
u	transformed variable
x_m	height of middle rectangular section of tube wall connecting semicircular section to quarter circular section, cm
y_1	distance from top of middle rectangular section of tube wall to interface of cladding and rectangular section, cm

- y_{1b} distance from bottom of middle rectangular section of tube wall to lower end of braze, cm
- θ center angle of semicircular tube section measured clockwise from vertical line of tube symmetry
- φ dummy variable

Subscripts:

- b region at back near flat surface of D-shaped cooling tube
- c coolant
- G gas
- m rectangular side of D-shaped cooling tube
- 0 crest of tube, $\theta = 0^\circ$
- 1 inner surface of D-shaped wall section, except y_1 and y_{1b} defined separately
- 2 outer surface of D-shaped wall section
- 3 outer surface of cladding material

ANALYSIS

Tube Configuration and Material

Hot gases flow along a wall made of tubes placed side by side and brazed together longitudinally. Each tube has the cross section shown in figure 1. Cladding material is placed over the outer radius of the tube r_2 and is assumed to follow the semicircular shape of the basic tube until it intersects the cladding from the adjacent tubes. The spacing between adjacent tubes was fixed at 0.00508 centimeter. (Nonsignificant figures were retained for calculation purposes.) This space was assumed to be filled with copper braze material. Coolant flows through the tube to lower the temperature of the tube wall to an acceptable value.

Two geometrical cases were studied: first, the basic tube made with either 347 stainless steel or copper; and secondly, the basic stainless tube with copper cladding, as shown in figure 1.

The outer radius r_2 of the basic tube was varied as well as the cladding and basic tube-wall thicknesses. The height of the rectangular section of the tube wall x_m was fixed at 0.1080 centimeter. Complete dimensions are shown in tables I and II. The radius of the quarter section of the tube wall was fixed at 0.0762 centimeter when the basic tube material was 347 stainless steel. This was permissible because the tube-

wall thickness was not varied over a large range. However, when the tube material was copper, strength considerations dictated thicker tube materials which in turn required a larger radius at the quarter section. These dimensions are shown in table I(b). The basic tube-wall thickness was determined from strength considerations. The fillet heights at the top of the tube Y_1 and at the back of the tube Y_{1b} required by the computer program (ref. 5) are given in tables I and II.

The temperature of the basic tube material is a maximum at the crest of the tube, and this will determine the stress limit placed on the coolant tube. The problem therefore is to calculate the tube-wall crest temperature and to determine the effect of the cladding and tube material on this temperature.

Assumed Operating Conditions

The heat-transfer conditions used for the calculations correspond to those which exist at the throat of a hydrogen-oxygen rocket engine having a throat diameter of 12.70 centimeters operating at a chamber pressure of 2.068 meganewtons per square meter (20.41 atm) using liquid hydrogen as the coolant.

The hot gas side heat-transfer coefficient h_G was in one case assumed to be constant ($6.47 \text{ kW}/(\text{m}^2)(\text{K})$). In the other case, based on experimental work of reference 6, the coefficient was assumed to follow a cosine variation with the center angle θ measured from the crest of the tube (i. e., $h_G = 6.47 \cos \theta$, $\text{kW}/(\text{m}^2)(\text{K})$). These two cases represent the extremes to be expected for the coefficient in a tubular walled rocket engine. The coolant side convective heat-transfer coefficient h_c was assumed to be constant ($39.42 \text{ kW}/(\text{m}^2)(\text{K})$) around the entire inner wall surface. In this work, for simplicity, the coolant coefficient was held constant even though the passage dimensions varied from one set of calculations to another. The hot gas and coolant temperatures were fixed at 3361 and 44 K, respectively.

Using materials that are compatible with both the hot gas and the coolant is necessary. Copper has been used successfully for heat sink type hydrogen-oxygen rocket engines. The copper temperature was of the order of 1000 K (ref. 7). Copper has been used in small scale liquid oxygen and JP-4 rocket engines at NASA Lewis Research Center. These engines have proved serviceable. The use of copper-clad stainless-steel tubes has been demonstrated in a hydrogen-oxygen regeneratively cooled rocket engine cooled with liquid hydrogen. Copper - stainless-steel interface temperatures of the order of 550 K were measured in this engine with no detrimental effect to the copper cladding (ref. 8). Based on this experience the use of copper as a cladding material or tube-wall material seems reasonable. For use with environments other than those just discussed, tests of corrosion, erosion, and strength should be performed.

Method of Computing Wall Temperatures

The tube-wall temperatures were computed using the method reported in reference 5. A brief summary of the basic equation and boundary conditions, along with the general method used to solve the equation for the wall temperatures, is given here. Details of the solution are given in reference 5.

The two-dimensional steady-state heat conduction equation

$$\nabla \cdot [K(T)\nabla T] = 0$$

with the boundary conditions

$$-K(T) \frac{\partial T}{\partial n} = h_G(T_G - T) \quad \text{on hot gas boundary (fig. 1)}$$

$$-K(T) \frac{\partial T}{\partial n} = h_c(T_c - T) \quad \text{on coolant boundary (fig. 1)}$$

$$\frac{\partial T}{\partial n} = 0 \quad \text{on boundaries which are lines of symmetry, and on outer boundary of lower quarter section of tube}$$

where

$K(T)$ thermal conductivity of material as function of temperature

$\partial T/\partial n$ temperature gradient perpendicular to wall surface

was transformed by the Kirchoff transformation (ref. 9, sec. 2.1)

$$u = \int_{T_{\text{Ref}}}^T K(\varphi) d\varphi \quad (1)$$

to give

$$\nabla^2 u = 0 \quad (2a)$$

$$-\frac{\partial u}{\partial n} = h_G(T_G - T) \quad (2b)$$

$$-\frac{\partial u}{\partial n} = h_c(T_c - T) \quad (2c)$$

$$\frac{\partial u}{\partial n} = 0 \quad (2d)$$

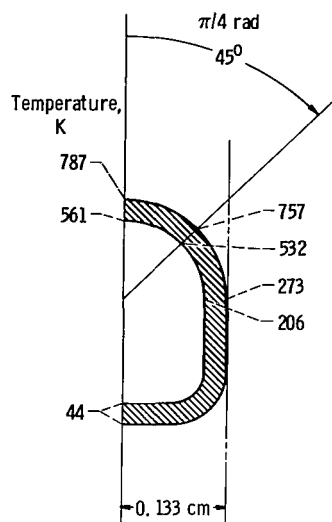
The symbol u is defined by equation (1), and equations (2a) to (2d) are obtained from the two-dimensional steady-state heat conduction equation and its related boundary conditions given previously.

A numerical solution of equation (2a) and its associated boundary conditions was obtained by the method of finite difference. A computer generated grid was superimposed on the region shown in figure 1, and at each interior point of the grid equation (2a) was approximated by the usual five-point difference scheme (ref. 10). The resulting difference equations were solved by successive line overrelaxation (ref. 10, sec. 6.4). The nonlinear boundary conditions (eqs. (2b) and (2c)) were linearized by means of a truncated Taylor series and approximated by forward differences. The difference equations for the boundary points were then solved by successive point overrelaxation. After a converged solution had been obtained for equation (2a) the temperatures T were calculated at each point of the grid by applying Newton's method to equation (1).

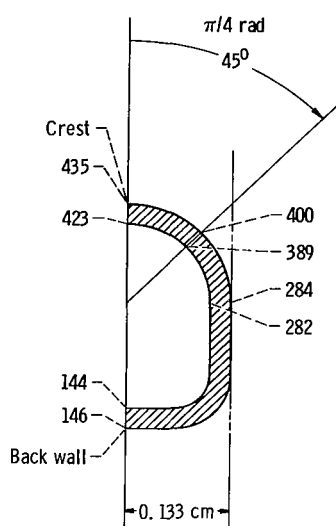
The geometrical input necessary for the program (given in ref. 5) is given in tables I and II. The thermal conductivity of 347 stainless steel and copper are given in reference 11 for cryogenic temperatures and in reference 12 for the higher temperatures. The thermal conductivity of the wall material as a function of temperature was approximated by fifth-order polynomials. An IBM 7094/7044 DCS computer programmed with HETTRAN, the program reported in reference 5, was used to compute the wall temperature distribution.

RESULTS AND DISCUSSIONS

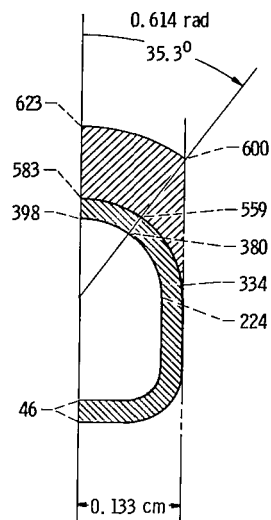
Scale drawings of the two extremes in semicircular tube radius ($r_2 = 0.133$ and 1.27 cm) with selected wall temperatures are shown in figure 2. The temperatures at several locations on the tubes are labeled in the figure to indicate the temperature distributions for the copper-clad stainless-steel, plain copper, and plain stainless-steel tube configurations. As shown in figure 2(a), the small tube ($r_2 = 0.133$ cm) has a rather large cladding thickness compared to the stainless-steel tube-wall thickness. This thickness gave the minimum tube-wall crest temperature T_3 at the cladding sur-



347 Stainless-steel tube

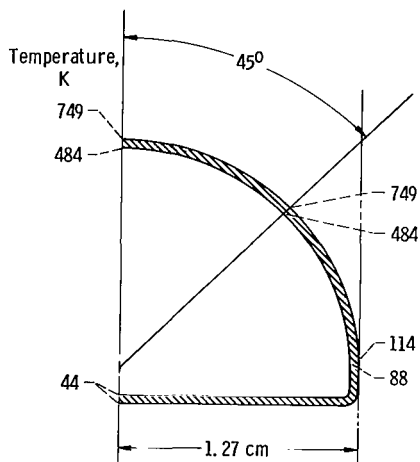


Copper tube

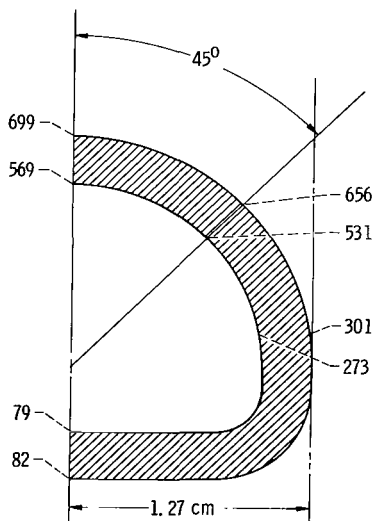


Copper-clad 347 stainless-steel tube

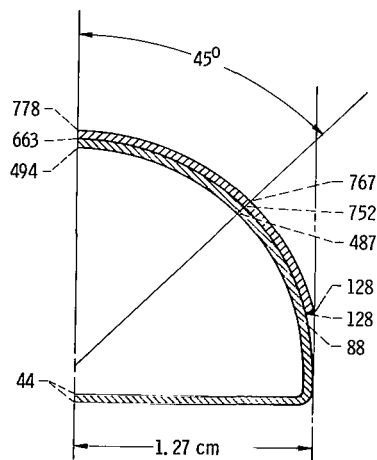
(a) Tube outer radius, $r_2 = 0.133$ centimeter.



347 Stainless-steel tube



Copper tube



Copper-clad 347 stainless-steel tube

(b) Tube outer radius, $r_2 = 1.27$ centimeters.

Figure 2. - Scale drawings with selected wall temperatures for copper-clad 347 stainless-steel cooling tube, plain copper tube, and 347 stainless-steel tube. Hot gas side heat-transfer coefficient held constant.

face. In light of present day electroforming techniques the large cladding thickness does not appear to be a problem. Thinner claddings yield tube-wall crest temperatures which are between those of the plain stainless-steel tube and the copper-clad tube shown in figure 2(a).

The plain copper tube shows the effect of conduction by having a back wall temperature higher than the coolant temperature. The back wall temperatures of both the clad and plain stainless-steel tube essentially equal the coolant temperature showing that tube-wall circumferential conduction is not as dominant a factor in these cases as it is for the plain copper tube. The plain copper tube has lower tube-wall crest temperatures than either the plain or clad stainless-steel tubes. These conditions exist for both the small ($r_2 = 0.133$ cm, fig. 2(a)) and large ($r_2 = 1.27$ cm, fig. 2(b)) radii tubes. Figure 2(b) shows the relative increase in tube-wall thickness required for strength consideration when using the plain copper tube compared to the plain stainless-steel tube.

The circumferential variations of the surface temperature for copper-clad 347 stainless-steel tube, plain copper tube, and plain 347 stainless-steel tube are shown in figure 2. The tube-wall crest temperatures of the smaller copper-clad tube (fig. 3(a))

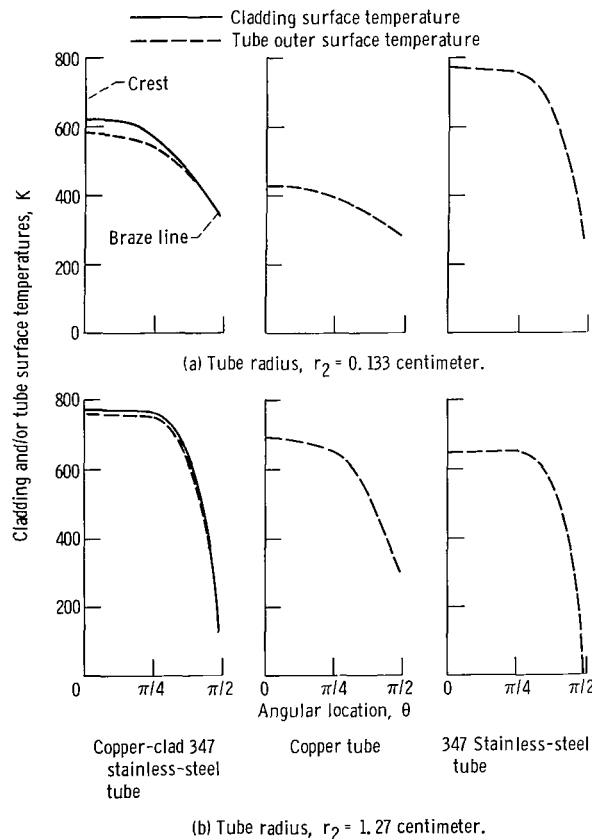


Figure 3. - Surface temperatures as functions of angular location θ from the crest ($\theta = 0$) of the tube. Constant gas convective heat-transfer coefficient (k_G).

are lower than the plain stainless-steel tube, while braze line temperatures of the copper-clad tube are higher. This is a direct result of the conduction of heat through the copper cladding to the braze line. In the case of the larger tube radius (fig. 3(b)), the tube-wall crest temperature of the copper-clad stainless steel is higher than that of the plain stainless-steel tube. The braze line temperatures show the same trend as the smaller tube radius, that is, elevated temperature at the braze line with copper cladding present.

The tube-wall crest temperatures T_1 , T_2 , and T_3 for all geometries investigated are given in tables I and II. Where feasible, an optimizing procedure was used which varied either the plain copper tube-wall thickness (table I(b)) or the copper cladding thickness (table II) to determine a minimum surface temperature. The minimum tube-wall crest temperature was obtained when the effect of circumferential conduction was off set by the increased one-dimensional resistance of the wall due to the wall or cladding thickness increase. The results of varying the plain copper tube wall thickness are shown in figure 4 for tube outer radii of 1.27 and 0.133 centimeter.

In the case where the tube outer radius is $r_2 = 0.133$ centimeter, a minimum tube-wall crest temperature, based on tube outer radius temperature, was obtained at a wall thickness of 0.040 centimeter. In the case where $r_2 = 1.270$ centimeters, an optimum tube-wall crest temperature was not obtained when tube thickness was varied. Since

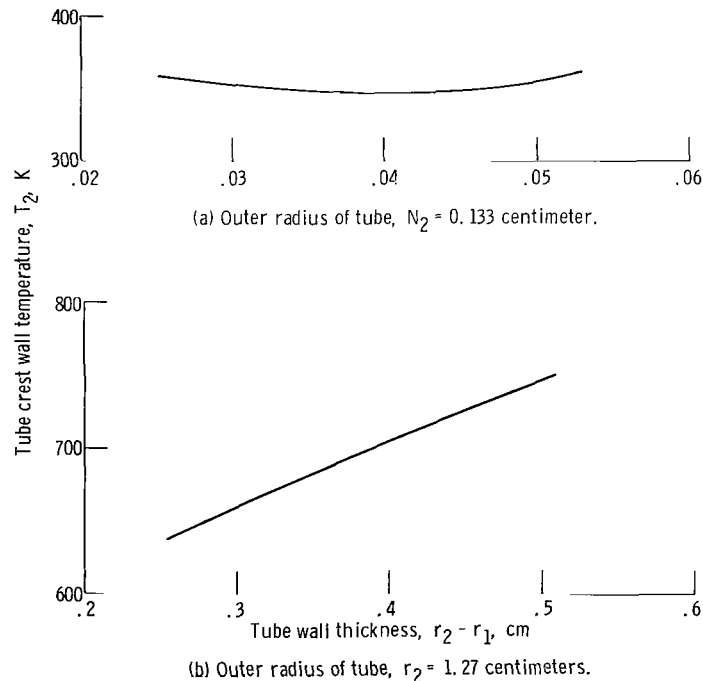


Figure 4. - Tube crest wall temperature as function of tube wall thickness. Copper tube material; heat-transfer coefficient on hot gas side of tube, $6.47 \cos \theta$ kilowatts per square meter times degrees kelvin.

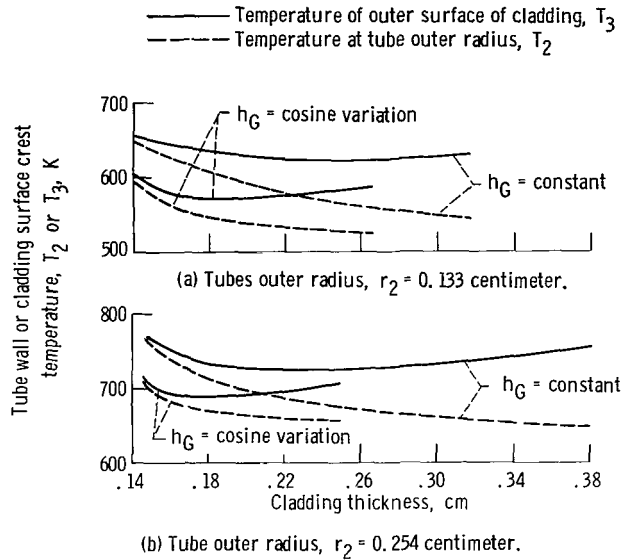


Figure 5. - Tube crest temperatures at outer radii of stainless steel and crest temperatures of cladding as function of cladding thickness.

the minimum wall thickness was selected on the basis of strength, it appears that a minimum tube-wall crest temperature does not exist for the larger radius copper tube.

Shown in figure 5 is a plot of the tube-wall crest temperatures at the cladding surface T_3 and the copper - stainless-steel interface T_2 as a function of cladding thickness. The temperatures are shown for the basic tube radius $r_2 = 0.133$ centimeter in figure 5(a). As the copper cladding thickness is increased, the cladding surface tube-wall crest temperature T_3 decreases to a minimum value (cladding thickness equals 0.229 cm where h_G is constant and 0.171 cm for the cosine variation) and then increases. The tube-wall crest outer and inner radii temperatures T_2 and T_1 decrease throughout the range of cladding thicknesses used in this investigation. This condition held true for both the constant and cosine variations of the hot gas side coefficient.

The variation of tube-wall crest temperatures with cladding thickness for a tube radius r_2 of 0.254 centimeter is shown in figure 5(b). The cladding thicknesses were again varied to determine the minimum crest cladding surface temperature T_3 . The minimum occurred at a cladding thickness of 0.121 centimeter for h_G constant and 0.070 centimeter for the cosine variation. For larger semicircular tube radii (r_2) of 0.635 and 1.270 centimeters (see table II(b)), a minimum crest cladding surface temperature T_3 did not exist and the basic tube outer radius temperature T_2 did not vary greatly.

The optimum (or minimum) tube-wall crest temperatures are shown in figure 6 as a function of tube outer radius r_2 for the plain stainless-steel, plain copper, and the copper-clad stainless-steel tubes. The temperature of the 347 stainless steel, which

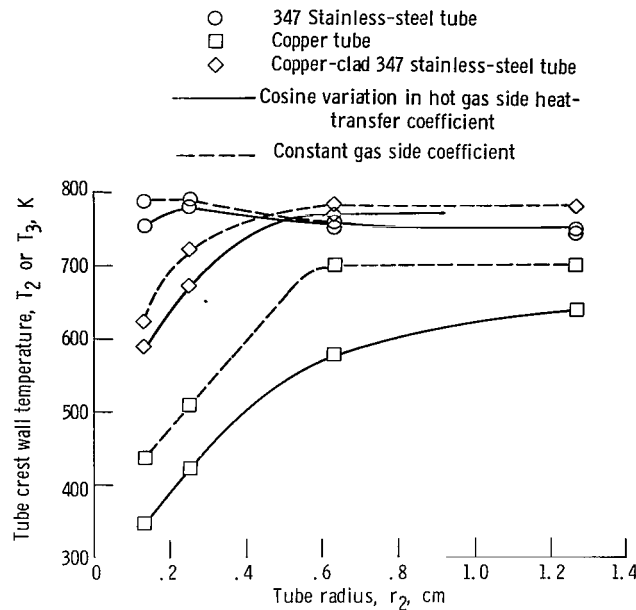


Figure 6. - Wall temperature at crest of basic tube as function of tube radius. Basic tube wall materials of copper and 347 stainless steel and composite of 347 stainless steel with copper cladding.

has a low thermal conductivity compared with copper, is hardly affected by the tube radius or the variation of the convective coefficient on the hot gas side.

The minimum tube-wall crest temperature T_2 for the plain copper tube is shown in figure 6. It is apparent that a significant lowering of the tube-wall crest temperature can be obtained by using copper as the tube material and using a small tube radius. This effect for the given heat-transfer conditions used for these calculations appears to be significant for tube radii less than 0.6 centimeter. The cosine variation of the hot gas side convective heat-transfer coefficient enhances this effect and shows a lower tube temperature than the constant coefficient calculation.

The optimum, or, where applicable, minimum crest cladding temperatures T_3 have also been plotted in figure 6 as functions of semicircular tube radius (r_2) for the copper-clad 347 stainless-steel configuration. Again, both the cosine and constant hot gas side heat-transfer coefficient cases have been shown. The clad tube temperatures fall between the stainless-steel and copper tube temperatures except for the larger tube radius values. The tube radius at which the clad tube-wall crest temperature exceeds the plain stainless-steel tube temperature marks the end of the range of tube radii in which the conduction of heat circumferentially around the tube is effective. This occurs at a tube radius of 0.45 to 0.50 centimeter.

It appears from figure 6 that a decrease of the basic tube-wall crest temperature of up to 150 K is possible if the tube radius r_2 is small. If the cladding material thick-

ness is allowed to increase past its optimum value, as seen in figure 5, temperatures (T_2) on the basic stainless-steel tube material will decrease even further and may be as much as 200 K lower than the plain stainless-steel tube.

CONCLUDING REMARKS

It should be pointed out that any application of coatings to cooling tubes or the use of copper or similar high thermal conductivity materials will require that calculations be made for the specific case under study.

It appears that extending the copper cladding to cover the entire outer surface of the tube would cause the stainless-steel tube-wall crest temperature to approach but not attain the tube-wall crest temperature calculated for the all copper tube, provided the tube radius is small. In effect this amounts to electroforming a copper tube on the outer surface of the stainless-steel tube. The sides of this composite wall would then conduct a portion of the heat around to the back of the coolant passage then into the coolant. The calculations carried out for the plain copper tube represent a lower limit of the tube-wall crest temperature for such a composite cooling passage.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 24, 1971,
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TABLE I. - WALL DIMENSIONS AND CREST TEMPERATURES FOR D-SHAPED PASSAGES

[Tube height, $x_m = 0.1080$ cm.](a) 347 Stainless steel tube material (tube spacing, $f_K = 0.00254$ cm)

Heat-transfer coefficient variation	Inner radius of tube, r_1 , cm	Outer radius of tube, r_1 , cm	Tube wall thickness, cm	Fillet height top, y_1 , cm	Fillet height bottom, y_{1b} , cm	Tube radius bottom, r_{2b} , cm	Crest temperature for	
							Tube inner radius, T_1 , K	Tube outer radius, T_2 , K
Constant	0.108	0.133	0.025	0.0320	0.0241	0.0762	561	787
Cosine	.108	.133	.025	.0320	↓	↓	529	754
Constant	.224	.254	.030	.0439	↓	↓	524	790
Cosine	.224	.254	↓	.0439	↓	↓	513	779
Constant	.605	.635	↓	.0696	↓	↓	493	758
Cosine	.605	.635	↓	.0696	↓	↓	492	757
Constant	1.240	1.27	↓	.0983	↓	↓	484	749
Cosine	1.240	1.27	↓	.0983	↓	↓	483	748

(b) Copper tube material (tube spacing, $f_K = 0.0241$ cm)

Heat-transfer coefficient variation	Inner radius of tube, r_1 , cm	Outer radius of tube, r_2 , cm	Tube wall thickness, cm	Fillet height top, y_1 , cm	Fillet height bottom, y_{1b} , cm	Tube radius bottom, r_{2b} , cm	Crest temperature for	
							Tube inner radius, T_1 , K	Tube outer radius, T_2 , K
Constant	0.108	0.133	0.025	0.0320	0.0241	0.0762	423	435
Cosine	.108	↓	.025	↓	↓	↓	346	357
	.093	↓	.040	↓	↓	↓	329	346
	.080	↓	.053	↓	↓	↓	338	361
Constant	.203	.254	.051	.0439	↓	↓	484	508
Cosine	.203	.254	.051	.0439	↓	↓	399	422
Constant	.508	.635	.127	.0696	.0439	.254	551	616
Cosine	.508	↓	.127	↓	.0439	.254	474	534
Constant	.381	↓	.254	↓	.0622	.508	569	699
Cosine	.381	↓	↓	↓	↓	↓	459	577
Constant	1.016	1.270	↓	.0983	↓	↓	569	699
Cosine	1.016	↓	↓	↓	↓	↓	514	637
	.889	↓	.381	↓	.0762	.762	513	697
	.762	↓	.508	↓	.0879	1.016	509	751

TABLE II. - WALL DIMENSIONS AND CREST TEMPERATURE FOR COPPER-CLAD

347 STAINLESS-STEEL TUBE CALCULATIONS

[Fillet height bottom, $y_{2b} = 0.0241$ cm; tube radius bottom, $r_{2b} = 0.0762$ cm; tube spacing, $t_K = 0.00254$ cm.]

(a) Wall thickness, 0.0254 cm; tube height, $x_m = 0.1080$ cm

Heat-transfer coefficient variation	Inner radius of tube, r_1 , cm	Outer radius of tube, r_2 , cm	Cladding thickness, cm	Fillet height top, y_1 , cm	Temperature for			
					Tube inner radius, T_1 , K	Tube outer radius, T_2 , K	Outer surface of cladding, T_3 , K	
Constant	0.108	0.133	0.146	0.032	462	665	671	
			.159		446	646	656	
			.165		433	628	641	
			.178		423	614	633	
			.191		414	603	627	
			.203		409	597	626	
			.216		403	588	624	
			.229		398	583	623	
			.241		395	578	624	
			.267		388	569	627	
			.279		385	565	629	
			.292		382	562	631	
			.305		380	558	634	
			.381		371	547	657	
			Cosine		.146	417	609	615
					.159	398	583	594
.171					390	573	588	
.184					387	568	588	
.197					384	564	590	
.210					382	562	593	
.222					380	558	595	
.235					380	559	601	
.248					378	556	604	

(b) Wall thickness, 0.0305 cm; tube height, $x_m = 0.1067$ cm

Heat-transfer coefficient variation	Inner radius of tube, r_1 , cm	Outer radius of tube, r_2 , cm	Cladding thickness, cm	Fillet height top, y_1 , cm	Temperature for					
					Tube inner radius, T_1 , K	Tube outer radius, T_2 , K	Outer surface of cladding, T_3 , K			
Constant	0.224	0.254	0.019	0.0439	491	747	756			
			.044		471	721	741			
			.070		454	698	729			
			.095		441	681	723			
			.121		432	668	721			
			.146		424	658	722			
			.171		418	651	726			
			.197		413	643	730			
			Cosine				.019	452	696	704
							.044	422	657	676
.070	412	643		672						
.095	407	635		676						
.121	403	630		681						
.146	400	626		688						
Constant	.605	.635		0.019			.0696	504	773	782
				.044				504	774	795
				.070				502	771	803
Cosine				.044			484	747	769	
			Constant	1.240	1.270	.032	.0983	494	763	778
.057	497	766				793				
.083	499	770				809				
			.108	502	773	825				

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